APPLICATION OF SMOOTHEST REFLECTANCE FUNCTIONS FOR THE VISUALIZATION OF SPECTRAL CHANGES DUE TO THE ILLUMINANT

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ABSTRACT

Given an RGB image of a visual scene presented on a color display, how would the scene look under a different illuminant? This question may be encountered in cases where a more or less realistic visualization is required or in psychophysical studies on topics like color constancy. A method is presented (based on existing technology) that does not require knowledge of the spectral reflectance functions of the objects in the scene. It uses the colorimetric calibration of the display to convert RGB values to CIE XYZ tristimulus values, makes an assumption about the illuminant, and applies van Trigt's [1,2] method for calculation of the smoothest reflectance function for each color in the image. The effect of changes in the spectral composition of the illuminant can then be calculated in terms of XYZ, and hence, can be visualized in RGB using the display calibration.

Keywords: *illuminant estimation, smoothest reflectance, visualization, spectral changes.*

1 INTRODUCTION

In daily life we are constantly confronted with imagery of visual scenes. These may originate from the 'normal' process of light reflection in which objects in the visual scene reflect the light from one or more light sources (illuminants), either natural or artificial ones. But more and more time is spent, both in work and leisure, looking at images displayed on light-emitting devices such as color television and computer monitors. With the increasing importance of the Internet for our society, this tendency may be expected to continue.

In cases where the displayed images are supposed to be realistic simulations of the true world of reflecting objects, we need complex models [3,4] that incorporate the physical principles of interaction between light and matter for a correct rendering of the image. But even when the models are available, the spatial and spectral distributions of the light emitted by the illuminant(s) and the distributions of object reflectances in the scene are not always known. So, realistic visualization of the effects of changes in the spectral composition of the scene (caused by changes in illumination or object properties) may be seriously handicapped by the lack of spectral information [5].

Camera systems exist that can measure, at pixel resolution, optical radiation in the full wavelength range relevant for human color vision. This is achieved, for instance, by using a monochromatic CCD camera in combination with different color filters [6]. Classical color filters can be fixed in a color wheel, but also tunable liquid crystal filters are now available that are electronically controlled [7]. This way the spectral sensitivities of the "channels" so created can be easily chosen and changed. Depending on the number of spectral channels this technique is called multi-spectral imaging (less than 10) or hyper-spectral imaging (up to several hundreds). Also line scan imaging spectrographs and interferometer based spectral imagers are commercially available [8,9]. The camera systems described above are relatively expensive and cannot be regarded as consumer electronics. Plain RGB cameras with spectrally broad and overlapping red, green and blue channel sensitivities still are the most widely used cameras. Therefore, pixel based spectral information of images is not widely available.

On the other hand, we seem to have no problem in watching a game of soccer on a color television screen, despite the fact that there is no exact colorimetric match between corresponding pixels in the television display and the soccer field. Apparently, we have a certain tolerance for colorimetric inaccuracy in the reproduction of images. Motivated by this tolerance, this paper presents a simple method for displaying color images under various illuminants with a high degree of realism. Although not perfect, it may be used for many visualization purposes, without requiring knowledge of the spectral reflections of the objects in the input image.

2 OUTLINE OF THE METHOD

The new method provides a practical answer to the following question. Given an arbitrary RGB color image of a visual scene, how would it look under a different illuminant? A sound colorimetric approach would require that, for each pixel in the image, the CIE XYZ tristimulus values have to be computed [10] according to

$$X = k\int_\lambda E(\lambda)R(\lambda)\bar{x}(\lambda)d\lambda$$
$$Y = k\int_\lambda E(\lambda)R(\lambda)\bar{y}(\lambda)d\lambda \qquad (1)$$
$$Z = k\int_\lambda E(\lambda)R(\lambda)\bar{z}(\lambda)d\lambda$$

in which E and R represent the illuminant and the (object) reflectance, $\bar{x}$, $\bar{y}$ and $\bar{z}$ are the color matching functions related to the standard (human) observer [10] - defined for 2 and 10 degrees of visual angle - and k is a normalizing factor. According to the guidelines of the CIE the integrals should be calculated over the wavelength region 380-780nm, although in most applications the range 400-700nm is sufficient. The integrals in (1) can be approximated by numerical summation, in which the spectral resolution depends on the desired level of accuracy [11].

Calculation of the tristimulus values implies full knowledge of the spectral power distribution of the illuminant and the spectral reflectance of the object "under the pixel" in question. However, both are often unknown. Therefore, two assumptions are made here. The first is that the light source that illuminated the original scene is daylight D65, the second is that the RGB image is displayed on a calibrated color monitor. The consequence of the first assumption is that the method will work best for images indeed recorded under daylight D65, but other illuminants (like equal energy) may be assumed as well. Also, in more refined methods the illuminant may be estimated from the average color in the image [12] or from the color of specific parts in the scene such as highlights [13]. The consequence of the second assumption is that the RGB values of the input image can be converted to device independent XYZ values by means of the known relationship between input value and output display luminance for each of the three color primaries [14]. Even when the colorimetric calibration of the display device is not known, a standard (average) calibration for that device may be adopted, such as sRGB [15].

Given the spectral power distribution of the illuminant, for each XYZ triplet (corresponding to a specific RGB triplet) in the image, there is still an infinite number of underlying possible reflectance spectra that satisfy eqn. (1). In this paper, this problem is tackled by application of an elegant method developed by van Trigt [1,2], in which the *smoothest* reflectance function is computed. Out of all possible reflectance functions that would result in the same XYZ (under the illuminant considered), the one is selected that varies most smoothly with wavelength. Smoothness is defined as the square of the derivative integrated over the visual range:

$$\int_\lambda \left(\frac{d\rho}{d\lambda}\right)^2 d\lambda = \text{minimal} \qquad (2)$$

The choice for smoothness is supported by the observation that practical, natural reflectance functions are also generally smooth [1].

After the spectral reflectance is determined, any change in the spectral composition of the illuminant can be shown by applying the standard colorimetric formulas for computation of (the changes) in X,Y and Z as given in eqn. (1). Finally, the new XYZ values are converted to RGB luminances using the display calibration and are generated on the display.

In principle, the method may be applied to each pixel in the image. In the implementation of the method in software and in the example shown in the next section, it was applied to the color palette of the image, after reducing the number of colors in the original image to 256. This was merely a matter of convenience. The calculation of the smoothest reflectance functions took about one second on a Pentium Pro personal computer with 192MB internal memory. The software was written in Visual Basic mainly for reasons of interfacing, but the code could certainly be optimized for speed in another programming language or by using a dynamic link library (DLL).

3 EXAMPLE

This section presents an example of the method, using an arbitrary image obtained from the Internet [16], and a specific monitor profile (that of the author's personal computer). The spectral power distributions of the illuminants used are shown in Figure 1. These were obtained by applying Planck's formula for a blackbody radiator at temperature 2500K and 4500K [10].

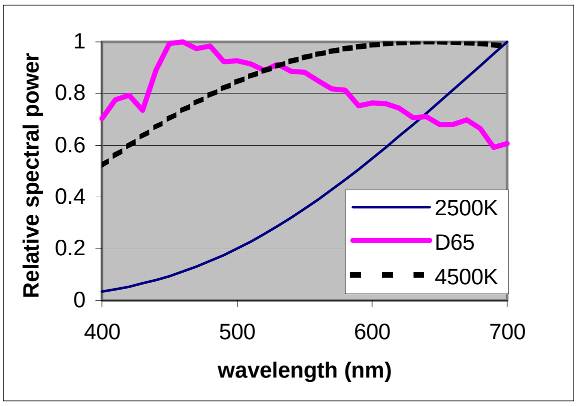

FIG. 1: Relative spectral power distributions of the illuminants used in the example (daylight D65 and blackbody radiators at temperature 2500K and 4500K).

FIG. 2: Example of the method described in section 2. The top image is the original image (assumed to be recorded under daylight D65 illumination) reduced to a 256 color bitmap, the middle and bottom images are the versions resulting for a simulated illuminant with color temperatures of 4500K and 2500K, respectively, mimicking the effect of a sunset.

4 DISCUSSION

The method presented does not have perfect color rendering properties, but this was never the intention. The method merely serves as a practical, straightforward solution to a complicated problem if no information about the spectral composition of an image is available. Nevertheless, it can compete with other methods for estimating surface reflectance properties. Troost & de Weert [17] tested this for a set of 2734 Munsell samples under nine different phases of daylight, and found that the color rendering performance of the van Trigt model is comparable to that of a linear model that employs Cohen's [18] spectral basis functions, the fundamental basis for many computational approaches to color constancy.

The assumption that the illuminant in the original scene is daylight D65 is probably too rough for certain images, in particular when they were captured under artificial light sources. However, recent work on the analysis of illuminant cues in two and three-dimensional images suggests that there is a special role for D65 in surface color perception [19]. As far as spatial non-uniformities in the illumination are concerned, these are assumed to be represented by the color and luminance changes in the original image. The method presented only responds to changes in the spectral contents of the illuminant, and as such operates as a color filter on the complete image. Whether or not this conforms to reality depends on the selected image.

One drawback of the method by van Trigt is that the mathematical problem of recovering the smoothest reflectance function for a XYZ triplet under a given illuminant has 16 types of solutions, each type being valid in a certain domain of color space. To guarantee that the smoothest reflectance function has reflectance values in between 0 and 1 for all wavelengths, there are restrictions on the values of X,Y and Z.

The method reported here has already proven its usefulness in a number of applied research projects where visualization of color effects was necessary. It was used for example to visualize how the world looks when wearing colored glasses and what difficulties with color discrimination can be expected in such situations.

Color constancy - the ability of our visual system to maintain a stable perception of object colors independent of the illuminant - is expected to break down in cases where the spectral power distribution of the illuminant is limited to a narrow wavelength region. This break down is predictable, however, and was experimentally verified using synthetic color patterns [20]. The method presented in this paper may be used to study color constancy with natural images.

5 SUMMARY AND CONCLUSIONS

A method is described that enables visualization of the effects of changes in the spectral composition of the illuminant, without knowledge of the spectral reflectances of the objects in the visual scene. Under the assumptions that the light source is daylight D65 and that the image is displayed on a calibrated color monitor, an existing method for calculating the smoothest reflectance functions is used. Although the color rendering properties of the method are not perfect, a fairly realistic visualization of illuminant changes on a broad range of images is obtained. The method has proven to be a valuable tool in a number of applied research projects.

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